Low-energy monopole strength in exotic nickel isotopes

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Low-energy strength is predicted for the isoscalar monopole response of neutron-rich Ni isotopes, in calculations performed using the microscopic Skyrme HF + RPA and relativistic RHB + RQRPA models. Both models, although based on different energy density functionals, predict the occurrence of pronounced monopole states in the energy region between 10 and 15 MeV, well separated from the isoscalar giant monopole resonance. The analysis of transition densities and corresponding particle-hole configurations shows that these states represent almost-pure neutron single hole-particle excitations. Even though their location is not modified with respect to the corresponding unperturbed states, their strength is considerably enhanced by the residual interaction. The theoretical analysis predicts the gradual enhancement of low-energy monopole strength with neutron excess.

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The multipole response of nuclei far from the β-stability line and the possible occurrence of exotic modes of excitation present a growing field of research. Besides being intrinsically interesting as structure phenomena, exotic modes of excitation might play an important role in r-process nucleosynthesis [1]. Low-lying $E1$ strength has been measured in neutron-rich oxygen, neon, and tin isotopes [2–4] and, more recently, in ^{68}Ni [5]. The interpretation of the dynamics of the observed low-energy $E1$ strength in nuclei with a pronounced neutron excess is currently under discussion (see Ref. [6] for a recent review). In light nuclei such as the oxygen isotopes the onset of dipole strength in the low-energy region is associated with nonresonant independent single-particle excitations of loosely bound neutrons. However, in the case of ^{68}Ni the low-lying dipole strength is found to be rather collective [7], and several theoretical analyses have predicted the existence of the pygmy dipole resonance (PDR) in medium-mass and heavy nuclei, i.e., the resonant oscillation of the weakly bound neutron skin against the isospin-saturated proton-neutron core. More recently, it has been shown that the low-lying $E1$ strength can exhibit a nontrivial pattern, separated into two segments with different isospin character. The more pronounced pygmy structure at lower energy is composed of predominantly isoscalar states with surface-peaked transition densities. At somewhat higher energy the calculated $E1$ strength is primarily of isovector character, as expected for the low-energy tail of the giant dipole resonance [8].

Of course, not only the dipole but also other multipoles could exhibit pronounced low-energy strength in neutron-rich nuclei. A theoretical study of the occurrence of pygmy quadrupole resonances has recently been reported in the framework of the quasiparticle-phonon model [9], and the monopole response in very exotic nuclei such as ^{60}Ca was investigated using the self-consistent Hartree-Fock calculation plus the random-phase approximation (RPA) with Skyrme interactions [10]. It was shown that near the drip line the monopole response could develop a very pronounced structure at low energy. The present study considers more realistic examples of nuclei in which the low-energy monopole strength could be measured in the near future. For the Ni isotopes, in particular, calculations of the monopole response in ^{78}Ni with the Gogny RPA did not predict pronounced low-lying strength [11], as evidenced from the percentage of the energy-weighted sum rule (EWSR) exhausted in the low-energy region. In Ref. [12] the monopole strength in nickel isotopes was studied using the Skyrme quasiparticle RPA (QRPA) approach with the SkM* functional. It is, however, difficult to discern a clear pattern in the low-energy region because of the large artificial smoothing factor. Here we study in more detail the occurrence of low-lying isoscalar monopole strength in neutron-rich Ni isotopes. In ^{68}Ni low-lying $E1$ strength has recently been measured [5]. A technique has been developed that enables the measurement of monopole strength in unstable nuclei [13]. An experiment has very recently been performed at Grand Accelerateur National d'Ions Lourds (GANIL) to measure the monopole strength in ^{68}Ni [14], and the analysis is in progress.

To minimize the model dependence of results, both Skyrme and relativistic energy density functionals are employed in the present analysis. Skyrme Hartree-Fock + RPA calculations are performed for the nuclei ^{68}Ni and ^{78}Ni, for which pairing effects are expected to play a negligible role in the monopole response. The description of the Skyrme HF + RPA approach can be found in numerous references [15–17] and will not be detailed here. We only mention that in this work RPA equations are solved in configuration space, and the particle-hole space is chosen so that the energy-weighted sum rule is fully exhausted. The continuous part of the single-particle spectrum is discretized by diagonalizing the HF Hamiltonian in a harmonic oscillator basis. An important quantity that characterizes a given state $\nu = (E_\nu, LJ)$ is its transition density:

$$\delta\rho^\nu(\mathbf{r}) \equiv \langle\nu|\sum_i \delta(\mathbf{r}-\mathbf{r_i})|\tilde{0}\rangle, \tag{1}$$

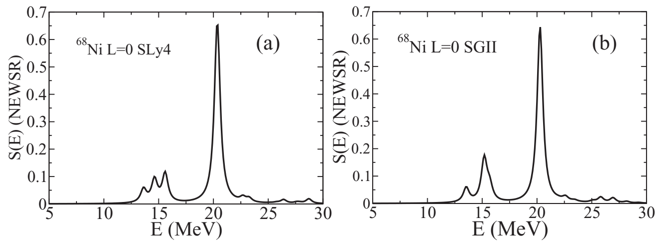

FIG. 1. Skyrme RPA isoscalar monopole strength functions in ^{68}Ni (in non-energy-weighted sum-rule units), calculated with the (a) SLy4 and (b) SGII energy density functionals.

with a corresponding definition of the neutron (proton) transition density $\delta\rho_n^\nu$ ($\delta\rho_p^\nu$) when the summation in Eq. (1) is restricted to neutrons (protons). A smoothing factor of 600 keV is used in plots of strength distributions.

The monopole response of Ni isotopes is also analyzed using the fully self-consistent relativistic quasiparticle random-phase approximation (RQRPA) based on the relativistic Hartree-Bogoliubov model (RHB) [18]. Details of the formalism can be found in Refs. [6,18]. In the RHB + RQRPA model the effective interactions are implemented in a fully consistent way. In the particle-hole channel effective Lagrangians with density-dependent meson-nucleon couplings are employed [19], and pairing correlations are described by the pairing part of the finite-range Gogny interaction. Both in the *ph* and *pp* channels, the same interactions are used in the RHB equations that determine the canonical quasiparticle basis and in the matrix equations of the RQRPA.

In Fig. 1 we display the isoscalar monopole strength in ^{68}Ni, calculated with the SLy4 [Fig. 1(a)] and SGII [Fig. 1(b)] nonrelativistic functionals. The giant monopole resonance (GMR) is calculated at about 20 MeV, and both functionals predict a pronounced low-lying structure located between 13- and 16-MeV excitation energy. For the response calculated with SLy4, the proton and neutron transition densities of the three states that compose the low-energy monopole structure are plotted in Fig. 2. These states are not purely isoscalar: the transition densities exhibit neutron-dominated modes, and the proton and neutron densities are not in phase in the interior of the nucleus. The configuration analysis of these states shows that they correspond to almost-pure single hole-particle excitations. A single configuration contributes more than 98% to the total strength: neutron $(2p_{3/2}, 3p_{3/2})$, $(2p_{1/2}, 3p_{1/2})$, and $(1f_{5/2}, 2f_{5/2})$ for the states located at about 13.6, 14.6, and 15.6 MeV, respectively. In nuclei that do not exhibit a pronounced neutron excess these $2\hbar\omega$ unperturbed configurations are located at higher energies, whereas in this case they are found below the GMR. The reason is that, because of the neutron excess in ^{68}Ni, the $3p2f$ states are located close to the Fermi level and, moreover, the $2p1f$ shell is calculated just below the Fermi level. This is not the case for the $3s2d$ shell. The $2\hbar\omega$ *sd* configurations that build the GMR are not lowered in energy, and therefore, the giant resonance is located at higher energy.

Figure 3 shows the RQRPA prediction for the isoscalar monopole response in ^{68}Ni, calculated with the relativistic functional DD-ME2 [20]. Despite a small difference in the predicted position of the GMR, the results for the low-lying part are very similar to those obtained with the Skyrme functionals, and the configuration analysis leads to the same conclusion about the noncollective character of these low-lying excitations. The comparison of the RQRPA spectrum with the unperturbed states shows that the residual interaction affects the strength but not the location of the low-lying states. They are well separated from the GMR, which in this relatively light nucleus is found at high energy. The corresponding proton and neutron transition densities are plotted in Fig. 4. The transition densities for the low-lying states at 12.16, 13.38, and 15.42 MeV (these states have the same particle-hole structure as the corresponding ones in the Skyrme RPA calculation) correspond to almost-pure neutron modes, and the radial dependence is very different from the typical isoscalar GMR transition densities exhibited by the collective state at 18.94 MeV. The enhancement of the low-lying monopole strength in the RQRPA case compared to the RHB one is due to a small increase of the magnitude of the neutron transition density,

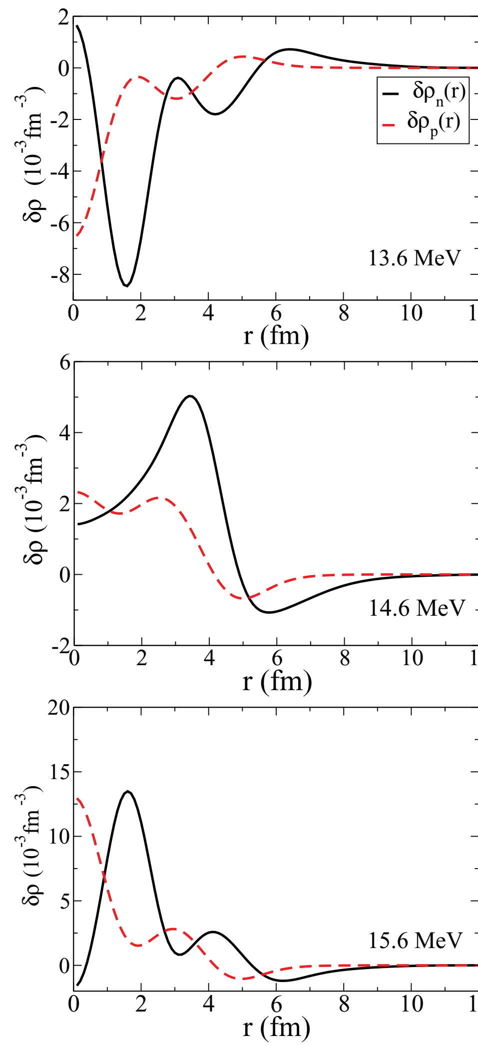

FIG. 2. (Color online) Skyrme RPA neutron (solid line) and proton (dashed line) transition densities for the three low-lying isoscalar monopole peaks at 13.6, 14.6, and 15.6 MeV in ^{68}Ni, calculated with the SLy4 functional.

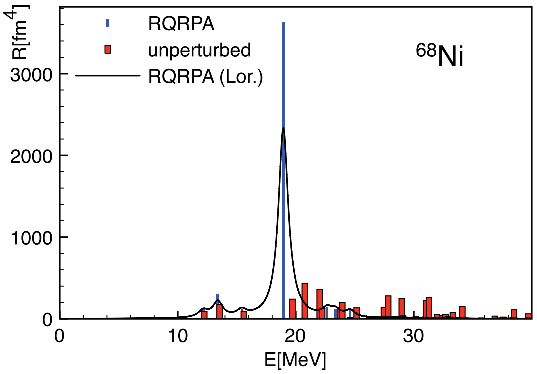

FIG. 3. (Color online) Monopole response of ^{68}Ni calculated using the RHB + RQRPA model with the DD-ME2 [20] functional. In addition to the RQRPA discrete spectrum and the corresponding Lorentzian averaged curve, the unperturbed spectrum is also displayed.

with the strength being a momentum of the transition density. Also, a slight admixture of neutron and proton configurations contributes to these states.

Similar results are also obtained for ^{78}Ni (Fig. 5), for which both Skyrme RPA and RHB + RQRPA calculations predict pronounced strength in the energy region around 15-MeV excitation energy, well separated from the GMR. The low-lying strength is more pronounced than in the case of ^{68}Ni. The overall structure predicted by the DD-ME2 functional is shifted to somewhat lower energy compared to

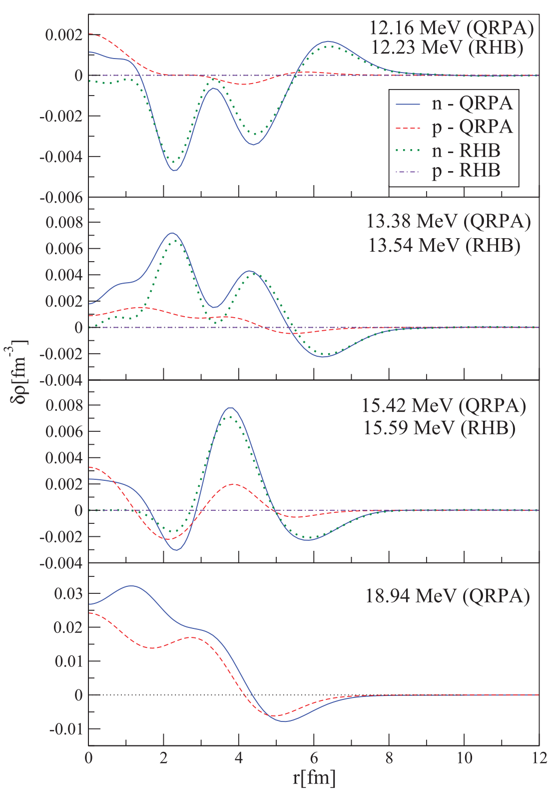

FIG. 4. (Color online) ^{68}Ni proton and neutron transition densities of the three low-lying RHB + RQRPA states at 12.16 MeV, 13.38 MeV, and 15.42 MeV, compared to those of the GMR at 18.94 MeV.

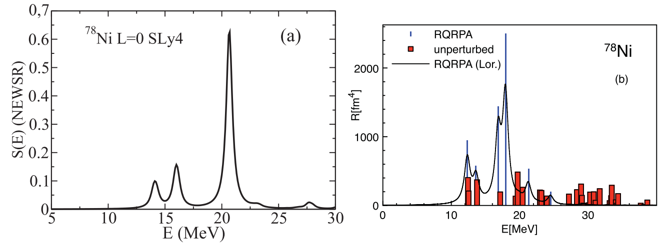

FIG. 5. (Color online) Monopole response of ^{78}Ni calculated using the Skyrme RPA model with the SLy4 functional (in non-energy-weighted sum-rule units) (a), and the RHB + RQRPA model with the DD-ME2 functional (b).

the one calculated with SLy4. The comparison between the unperturbed spectrum and the full RQRPA response nicely illustrates how the residual interaction builds the collective GMR from the states above 15-MeV excitation energy. The two low-lying unperturbed states are not lowered in energy, even though their strength is considerably increased by the inclusion of the residual interaction in the full relativistic RPA. To illustrate the evolution of low-energy monopole strength in Ni isotopes, in Fig. 6 we show the monopole response of even-A $^{60-78}$Ni isotopes calculated with RHB + RQRPA. One can clearly follow how the low-lying strength in the energy region between 10 and 15 MeV develops with the neutron excess. Since these states, predicted both by Skyrme RPA and RQRPA calculations, are noncollective, their occurrence essentially depends on the position of the neutron Fermi level in the single-neutron spectrum. The RPA strength contained in these states, however, is markedly enhanced by the residual interaction. These predictions point to a possibly very interesting measurement of low-lying isoscalar monopole states in neutron-rich Ni isotopes that would probe almost-pure single-neutron configurations. A resolution of approximately 2 MeV can currently be achieved with the experimental setup dedicated to the measurement of the monopole response in unstable nuclei [13]. An improvement to a 1-MeV energy resolution

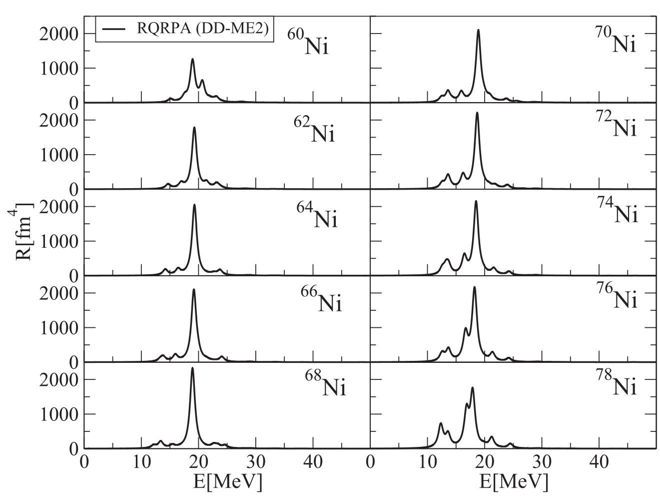

FIG. 6. Monopole response of even-A $^{60-78}$Ni isotopes calculated using the RHB + RQRPA model with the DD-ME2 functional.

is expected [14], and the development of next-generation active targets such as ACtive TARget (ACTAR) [21] will proceed along this path. It should be noted, however, that the physical width of the monopole response (the spreading width, the decay width, and the Landau damping) could also prevent a clear separation between different low-energy states.

In conclusion, fully self-consistent microscopic Skyrme HF + RPA and relativistic RHB + RQRPA calculations have been performed for the isoscalar monopole response in neutron-rich Ni isotopes, some of which should become experimentally accessible in the near future. Both the nonrelativistic and relativistic models, based on Skyrme functionals and the relativistic functional DD-ME2, respectively, predict the occurrence of pronounced low-energy monopole states in the energy region between 10 and 15 MeV, well separated from the isoscalar GMR. From the analysis of transition densities, transition matrix elements, and the particle-hole configurations that correspond to these states, it is evident that the low-energy monopole states represent almost-pure neutron single hole-particle excitations. Their occurrence can be related to the closeness of the corresponding orbitals to the neutron Fermi level in nuclei with large neutron excess. Even though their location is not modified with respect to the corresponding unperturbed states, their strength is considerably enhanced by the residual interaction. The theoretical analysis predicts an increase of low-energy monopole strength with neutron excess. A measurement of these states would provide direct information on the $2\hbar\omega$ gap and directly probe the single-particle spectrum in exotic neutron-rich nuclei, which is known to be driven by the spin orbit and the tensor terms of the effective internucleon interaction. In particular, measurements of the monopole strength in neutron-rich nickel isotopes are currently being performed, and this work will help to interpret the results.

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